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Chapter – **Feedbacks between internal and external Earth dynamics**

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Abstract

Countless continuously interacting processes determine the functioning and evolution of the Earth. Even geodynamic and climate changes, which have been classically studied independently because they pertain to different Earth 'spheres', are linked by mutual cause-effect relationships that recent research has just started to recognize and quantify. Modeling, be it analogue or numerical, is a trump card in this research for it allows rigorous integrations and interpretations of multiple observations that report on processes with different characteristic spatial and temporal scales and occurring at the Earth's surface or deep within its interior. In this solicited chapter, I let my academic journey thus far illustrate the challenges of the study of the feedbacks between internal and external Earth dynamics and its relevance for the Earth Sciences as well as for facing and mitigating ongoing fast and extreme global changes.

Keywords: Internal and external Earth dynamics; interactions between geodynamic and climate changes; geological carbon cycle; geological observations and modeling.

1. The ground up

My creed for the continental drifting and plate tectonics theories grew firm from 2003 to 2008, when I was a lucky undergraduate student of Earth Sciences at the State University of Milan. Knowing and believing, however, blend into some sort of flawed religious understanding when one learns passively. I first realized this in 2007 when I met Laurent Jolivet and Evgueni Burov in the frame of the Erasums Exchange at the Sorbonne Université and Ecole Normale Supèrieure in Paris. As a task for one of the exams, Laurent asked me to read the Burov & Diament, 1995, and Jackson, 2002, papers and present my understanding of the rheology of the continental lithosphere. The different perspectives involved by the 'jelly sandwich' and 'crème brulée' rheological models of the continental lithosphere and the arguments in support of and against these models helped me realize about patently unsolved and yet very fundamental issues in the plate tectonics and continental drift theories. During my stay in Paris, Laurent and Evgueni further showed me a different Geology from the classical observational and qualitative Science I was used to. They taught me the basis of a rigorous Geology oriented to the understanding of processes and interactions between processes through integration of quantitative analyses of geological observations.

The Deformation Mechanisms, Rheology and Tectonics (DRT) conference was held in Milan in 2007. As a student from the organizing Department, I could help with the organization of the meeting in exchange for free access to my first geological conference. The presentation by Taras Gerya, who showed numerical models of subduction and continental collision, impressed me particularly. Every frame of those physics-based 'movies' (literally the opposite of 'science fiction') of fundamental geologic processes showed structures extraordinarily similar to those I could observe in the European Alps, with the impressive addition of the stress and thermal fields in which they originate, an information that none of the many structural Alpine cross-sections I came across until then (models just as well) could provide. Once I graduated a few months later, I applied for all open PhD positions that involved numerical modeling of geologic processes. I was eventually offered a position by Sean Willett at ETH-Zurich to work on a project (part of the TOPO-EUROPE program, funded by the European Science Foundation) aimed at constraining the role of glaciation in affecting the Plio-Quaternary topographic and tectonic history of the Alps. I was trained as a 'classical' structural geologist and the focus on geomorphology was largely outside my comfort zone. I was also underestimating the considerable (but worthy) effort required to learn the basics of numerical modeling without an appropriate background. I learnt soon after that stepping out of your comfort zone and engaging into new and demanding challenges is exactly what research is about.

During the PhD, I was mainly supervised by Frédéric Herman who gave me what I now acknowledge as a fairly balanced amount of constraints and liberty to allow for independent and in depth learning. The learning process was facilitated by Matthew Fox, who came from Oxford to begin his PhD at the same time as me, but with a much better training in any sort of quantitative analyses. It did not take long to realize that surface processes - erosion and sediment deposition but also the formation and melting of continental ice-caps and associated sea level changes - are affected by but also affect the most relevant expressions of plate tectonics and, thus, are critical in determining the evolution of the Earth system. Simple physical considerations make this point easily understandable. The horizontal motion of tectonic plates implies their shortening or stretching, both of which involve vertical deformation of the Earth's surface plates. Thickening or thinning of tectonic plates 'floating' on the underlying mantle imply a departure from the equipotential state and, thus, work against the horizontal motion of plates (Fig. 1). The dismantling of uplifted terrains via erosion and the filling of subsiding basins with sediments contribute to restore the equipotential state, thereby facilitating the horizontal motion of plates and the associated strain. Within this frame, convergent mountain belts have been considered as crustal scale accretionary wedges in which deformation is described by a simple Coulomb behavior since the pioneering works by Davis, Dahlen, and Suppe in the 1980s (e.g., Davis, et al., 1983; Dahlen, et al., 1988). Sandbox numerical as well as analogue models show localized thrusting during convergence that controls the geometric, topographic, and architectural evolution of the wedge. Basal décollements play a major role allowing for the formation of duplex structures and underplating at different structural levels within the wedge, whereas frontal accretion characterizes the deformation in the foreland. The strong localization of brittle deformation in thrust wedges exerts a major influence on topography and, thus, on erosion. In turn, erosion and sedimentation decrease the topographic slope thereby favoring a change from overcritical to stable to undercritical mechanical state of the wedge (e.g., Willett, 1999) and allowing for a feedback loop that plays a particularly important role for what concerns exhumation of deep crustal and metamorphic rocks.

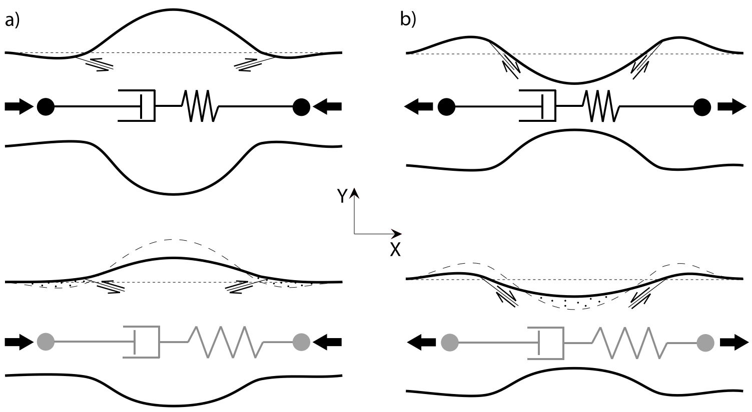

Figure 1: Schematic representation of the effect of surface processes on the stress state within a deforming continental lithosphere subject to horizontal compression (a) or shortening (b). Relaxed (gray) and stressed (black) visco-elastic systems are represented by an elastic spring and viscous damper. Surface processes relax deforming systems, thereby contributing to the restoration of the equipotential state lost due to horizontal and vertical tectonic strain.

For instance, analogue models allow relating many of the main structures within classical geological sections across the Swiss Alps to erosion and/or sedimentation during convergence (e.g., Malavieille & Konstantinovskaya, 2010; Fig. 2a-c). In response to shortening without surface processes, an analogue basement is commonly subject to initial thrusting and imbrication upon inherited structural and sedimentary weaknesses. Then, the homogenous part of the basement underthrusts and a high friction wedge is originated. With erosion and sedimentation, convergence leads to initial thrusting and frontal accretion in the foreland basin, followed by formation of an antiformal stack of duplexes in the internal part. Here, protracted strain localization, erosion and exhumation isolates a frontal synformal klippen of formerly imbricated thrust units and the antiformal structure eventually outcrops as a tectonic window, as observed in the natural case study (e.g., Burkhard & Sommaruga, 1998). The influence of surface processes on orogenic dynamics in the European Alps is also expressed at short timescales since at least ~50% of the geodetically measured present-day vertical displacements are currently ascribed to the deglaciation of the Last Glacial Maximum ice-sheet and Plio-Quaternary erosion of the belt (e.g., Sternai, et al., 2019, and references therein). Another example is provided by exhumation of the high-grade metamorphic Greater Himalayan Sequence along the Himalayan-Tibetan range, interpreted as the result of southward growth of the Tibetan plateau due to ductile flow in the middle to lower crust (e.g., Burchfiel, et al., 1992; Royden, 1996; Grujic, et al., 1996; Wu, et al., 1998). Thermo-mechanical numerical models, which further allow to account for the ductile behavior of rocks during convergence and flexure of the lithosphere due to the topographic growth and erosion or sediment deposition (e.g., Garcia-Castellanos, 2002), clearly indicate a dynamic link between the ductile flow and exhumation of lower crustal rocks and localized surface erosion at the orogen front where topographic slopes and orographic precipitations are particularly significant (e.g., Beaumont, et al., 2001; Zeitler, et al., 2001; Fig. 2d).

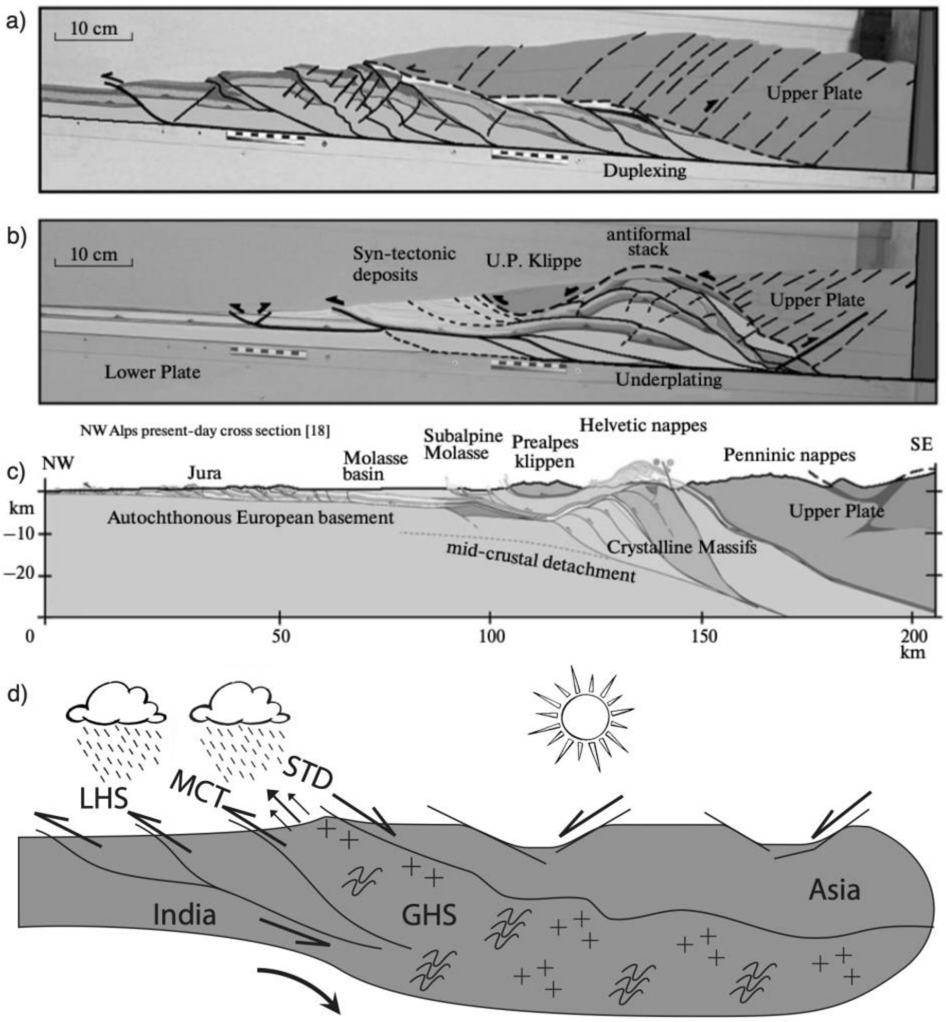

Figure 2: (a) Analogue models of crustal convergence and orogenic wedge evolution without (a) and with (b) erosion and syn-tectonic sedimentation (Malavieille & Konstantinovskaya, 2010). Modeling results are compared to a classical cross section of the Swiss Alps (c) from Burkhard & Sommaruga, 1998. d) Crustal tectonic framework of the Himalaya and Southern Tibet where erosion at the mountain front contributes to localized exhumation of weak lower crustal material (e.g., Wu, et al., 1998; Burchfiel, et al., 1992; Beaumont, et al., 2001). LHS, Lesser Himalayan sequence; MCT, Main Central Thrust; STD, South Tibetan Detachment; GHS, Greater Himalayan Sequence.

Thanks to an enormous amount of research performed in less than one generation, it is now established that deformation, surface uplift or subsidence and erosion or sediment deposition (these latter may act in addition to ice-building/melting or sea level changes) comprise a system with feedbacks that links plate tectonics and continental drifting to the evolution of the surface topography. Being the main driver of both the motion of tectonic plates and the redistribution of the surface masses, the gravity acceleration is the fundamental engine of the feedbacks between internal and external dynamics. Climate, however, has a special role to play because it determines the driving mechanisms of the redistribution of the Earth's surface masses and, thus, the rate at which the lost equipotential state due to the tectonic strain may be re-established (or re-approached to).

2. The ground down

In 2012, a few months before defending my PhD I contacted Laurent Jolivet to ask for postdoc opportunities in his research group. He replied quickly and positively since his RHEOLITH ERC Advanced Grant proposal had just been funded. The project involved a study of the rheology of the continental lithosphere based on three main pillars: field observations, experimental measurements, and numerical modeling. Laurent, who transitioned to the University of Orléans while I was a graduate student at ETH-Zurich, offered me a postdoc position to work on numerical modeling of subduction and collisional systems constrained by available and newly produced observational and experimental data. Because numerical modeling provides a means to test hypotheses formulated based on field observations, Laurent brought me in continental Greece and the Cyclades, where large-scale GPS measurements, seismic data and outcrop-scale strain structures allow observing continental chunks (e.g., Anatolia) being extruded out of a collisional system (e.g., the Bitlis-Zagros domain) into the back-arc domain of an active subduction system (e.g., the Aegean). These observations raised a number of considerations in my head. First, if continents extrude like toothpaste squeezed out the tube, they must be somewhat soft. Second, convergent settings involve more than just shortening, thickening and uplift of the surface topography. The assumption that a collisional orogen is a broad uniformly and steadily uplifting area, which I came across and adopted myself many times during my PhD, seemed a particularly coarse oversimplification ever since. Third, lateral boundaries of convergent settings are particularly important for they determine whether and where lateral escape of continental material can occur via transcurrent strain, thereby allowing the convergence to continue or forcing it to slow and eventually end. Indeed, in reducing the work against gravity that horizontal tectonics produces, extrusion tectonics play a very similar role to that of surface processes (Fig. 3a) and I refer again to the magnificent Tibetan plateau and mountains of Asia to provide an example.

The Tibetan-Himalayan range has been long ascribed to lithospheric shortening and thickening along the India-Eurasia margin (e.g., Argand, 1924; Molnar & Tapponnier, 1975). Unlike the abrupt Himalayan front, the gentler but still impressive topography along the eastern margin of Tibet developed in a predominantly trans-tensional tectonic regime (e.g., Leloup, et al., 1995; Wang, et al., 1998; Hall & Morley, 2004). These fundamental observations and the geophysical evidence suggesting the presence of a weak lower crust below Tibet (e.g., Nelson, et al., 1996; Xu, et al., 2007) triggered a debate about the partitioning between clock-wise rigid rotation (e.g., Tapponnier, et al., 1981; Armijo, et al., 1986; Avouac & Tapponnier, 1993; Leloup, et al., 1995; Meade, 2007) or viscous eastward evacuation of the Asian crust and lithosphere, possibly involving crustal channel flow (e.g., England & Houseman, 1986; Royden, 1996; Clark & Royden, 2000; Clark, et al., 2006; Copley & McKenzie, 2007). These proposals put different emphasis on strain localization, vertical gradients of strain due to depth-dependent rheologies, the role of gravitational body forces and tractions at the base of the lithosphere, and the influence of plate boundary dynamics, but all agree that extrusion tectonics permitted protracted and ongoing convergence of India into Eurasia. Similarly, common to all proposed models are a focus on crustal dynamics and, regarding the effects of plate boundary dynamics, the assumption that subduction of oceanic lithosphere along the Sunda and western Pacific margins created the accommodation space for unconstrained continental extrusion. I stress here that these considerations are not unique to the Asian mountains, but apply to many places along the Alpine-Himalayan orogenic belt, which is a continuous alternation between collisional (the Alpine-Dinarid, Bitlis-Zagros and Tibetan-Himalayan mountains) and subduction zones (Carpathian-Pannonian, Ionian-Aegean, Makran and Sunda subduction systems), toward which continental extrusion systematically takes place (Fig. 3b,c).

The necessary requirement of an ‘open’ boundary to allow for extrusion, be it by rigid rotation of upper crustal continental blocks or by viscous flow of lower crustal material, and protracted horizontal convergence of plates puzzled me particularly. Widespread extension across the Anatolian extruded continental domains as it transitions into the back-arc regions of the bounding rollbacking Aegean subduction zone suggests that a ‘suction’ toward the subduction zone facilitates extrusion of continental slivers and, thus, horizontal convergence in the collisional domain. This hypothesis was already proposed for the eastern Tibetan margin (e.g., Burchfiel & Royden, 1985; Jolivet, et al., 1990; Northrup, et al., 1995; Schellart & Lister, 2005; Royden, et al., 2008). With the I3ELVIS geodynamic model provided by Taras Gerya, we could validate its physical and geological feasibility building a setup that accounts for a collisional and an ocean-continent subduction domain (Sternai, et al., 2014; Sternai, et al., 2016b; Menant, et al., 2016; Roche, et al., 2018). In these experiments, a major bended strike-slip surface structure on the upper plate, geometrically and kinematically similar to the North Anatolian or Altyn-Tagh fault zones, joints compressive structures in the collisional zone to extensional structures in the back arc domain of the subduction system. The strike-slip structure, however, only develops when the subducting slab is subject to rollback during convergence, whereas compression occurs across the entire upper plate otherwise. The numerical models also provide access to deep levels, where basal lithospheric shearing due to the asthenospheric return flow associated with slab rollback facilitates the upper plate extensional strain in the back-arc of the subduction zone. These results allowed us to conclude that rollbacking subduction zones at the sides of a collisional domain not only provide ‘free space’ but also actively drive continental extrusion thereby promoting the horizontal convergence between the colliding continental plates, a conclusion that may apply (or may have applied in the geological past) to multiple extruded domains along the Neo-Tethyan margin, Fig. 3a (e.g., Sternai, et al., 2014; Sternai, et al., 2016b).

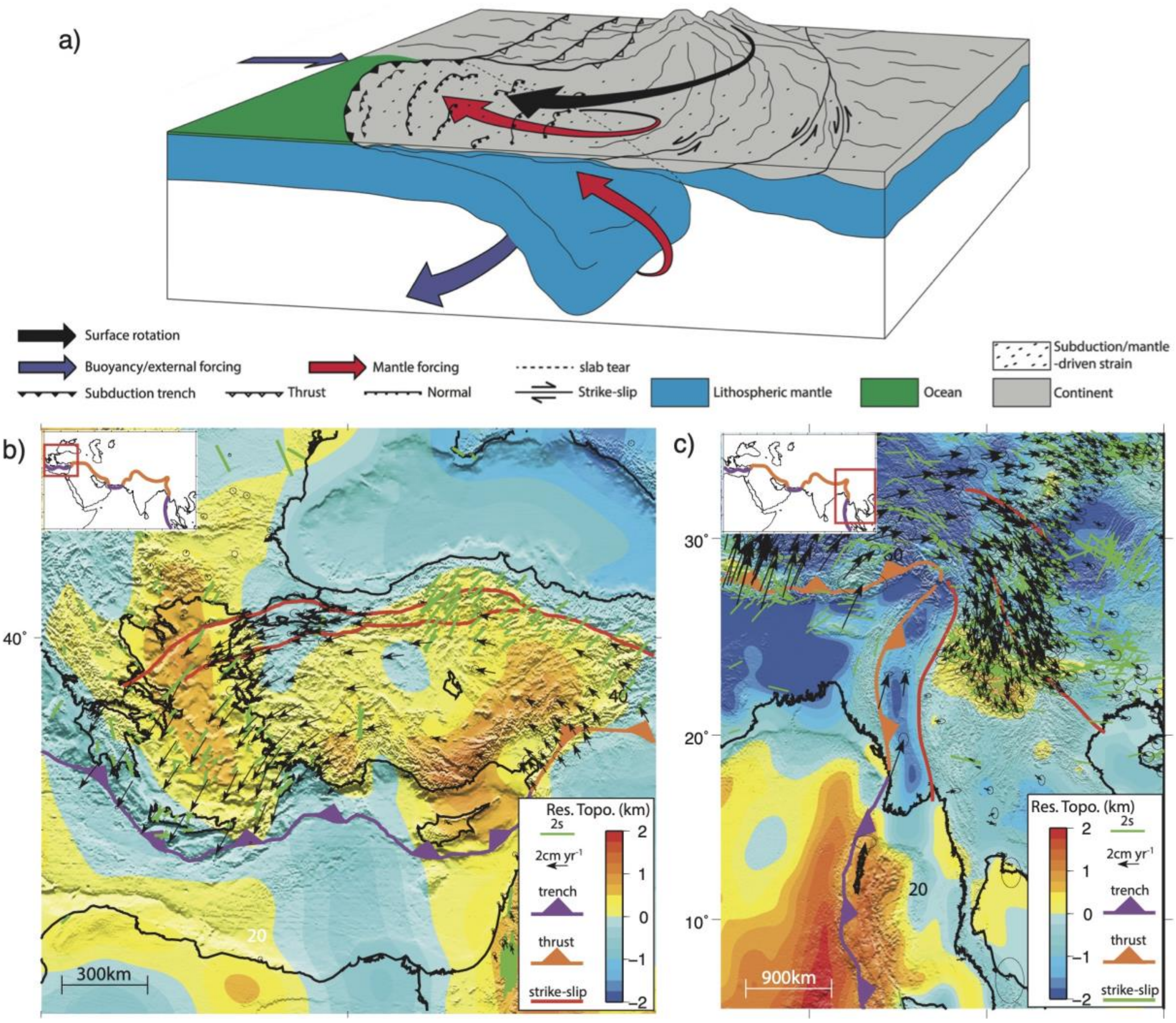

Figure 3: (a) Schematic representation of the dynamic interactions between continental collision, oceanic subduction, mantle flow and surface deformation (modified after Sternai et al., 2014). (b) Maps of the residual topography, $z_{res} = z_{obs} - z_{iso}$. The surface elevation of a lithospheric column with respect to a reference elevation, H, is determined by $z_{iso} = ((\rho_a - \rho_c)/\rho_a l_c + (\rho_a - \rho_m)/\rho_a l_m)$-H, where l_c is the crustal thickness, ρ_c is the average crustal density, l_m is the lithospheric mantle thickness, ρ_m is the average mantle lithosphere density, and ρ_a is the asthenosphere average density. Maps where generated based on the CRUST1.0 model and assuming a lithospheric thickness of 100 km, uniform crustal and mantle densities and H equal to the average mid-oceanic ridge elevation (e.g., Lachenbruch & Morgan, 1990). More details on the methodology can be found in Faccenna, et al., 2014; Sternai, et al., 2016b; Sternai, et al., 2019. Positive values across extruded continental domains suggest that differential along-strike kinematics at the transition between subduction and collision zone along the Neo-Tethyan margin may produce vigorous asthenospheric flow that contributes to the surface strain and topographic uplift. GPS velocity vectors are from Zhang, et al., 2004; Gan, et al., 2007; Reilinger, et al., 2010. Seismic anisotropies (green markers) are from Wüstefeld, et al., 2009, and Biryol, et al., 2010.

In 2013, Jean Philippe Avouac and his students from Caltech joined one of the fieldtrips to Greece and I had the chance to show the recently obtained numerical results and discuss our preliminary interpretation. Jean Philippe suggested to extract the vertical component of the asthenospheric return flow due to slab rollback and evaluate under which conditions the resulting stresses provide significant support to the topography of the extruded continental domains. A few months later he offered me a postdoc position to be held at Caltech and the University of Cambridge to study the relationships between basal lithospheric traction due to the asthenospheric flow and the surface evolution with a focus on Southeast Asia. The objective was to assess whether the asthenospheric return flow owing to protracted northward migration of the Indian indenter during rollback (late-Eocene to middle-Miocene) or stable (middle-Miocene to present) subduction along the Sunda and western Pacific margins (e.g., Tapponnier, et al., 1986; van der Hilst & Seno, 1993; Hall & Morley, 2004; Sibuet, et al., 2004; Honza & Tokuyama, 2004; Royden, et al., 2008; Replumaz, et al., 2013) could provide active support to the topography. Working with Jean Philippe helped me realize that, because complex 3D numerical geodynamic models can account for a multitude of processes and interaction between processes, the interpretation of the numerical results in terms of driving forces and resulting effects requires careful analyses. An analytical investigation of the numerical results in terms of Gravity Potential Energy (GPE) and depth-integration of strain and stress variations led to recognition that the asthenospheric flow due to differential along-strike slab kinematics may be vigorous enough to contribute to the surface strain and elevations at collision-subduction transition zones (Sternai, et al., 2016b; Fig. 3b,c). If large-scale mantle convection drives the overall India-Eurasia convergence (e.g., Alvarez, 2010; Becker & Faccenna, 2011), the more local asthenospheric return flow related to relatively shallow dynamics contributes to the topographic evolution, which indicates even tighter, smaller-scale and higher-order relationships between internal and external dynamics than previously recognized.

3. Merging concepts toward an integrative understanding of the Earth system

At the beginning of 2015, I have been invited by Sébastien Castelltort to give a seminar at the Department of Earth Sciences of the University of Geneva. At the end of the seminar, Luca Caricchi pointed out that, if erosion can change the stress field at depth so to modulate the strain pattern, it may also affect the magma production because pressure is key to partial rock melting in many geodynamic contexts. The following discussions with Luca and Sébastien led to recognition of a poorly explored and very promising link between internal and external dynamics: the coupling between surface processes and magmatism. I was approaching the end of my second postdoc and it was the right time to try my hand at writing a research proposal which, about a year later, the Swiss National Science Foundation funded in the frame of the 'Ambizione' program.

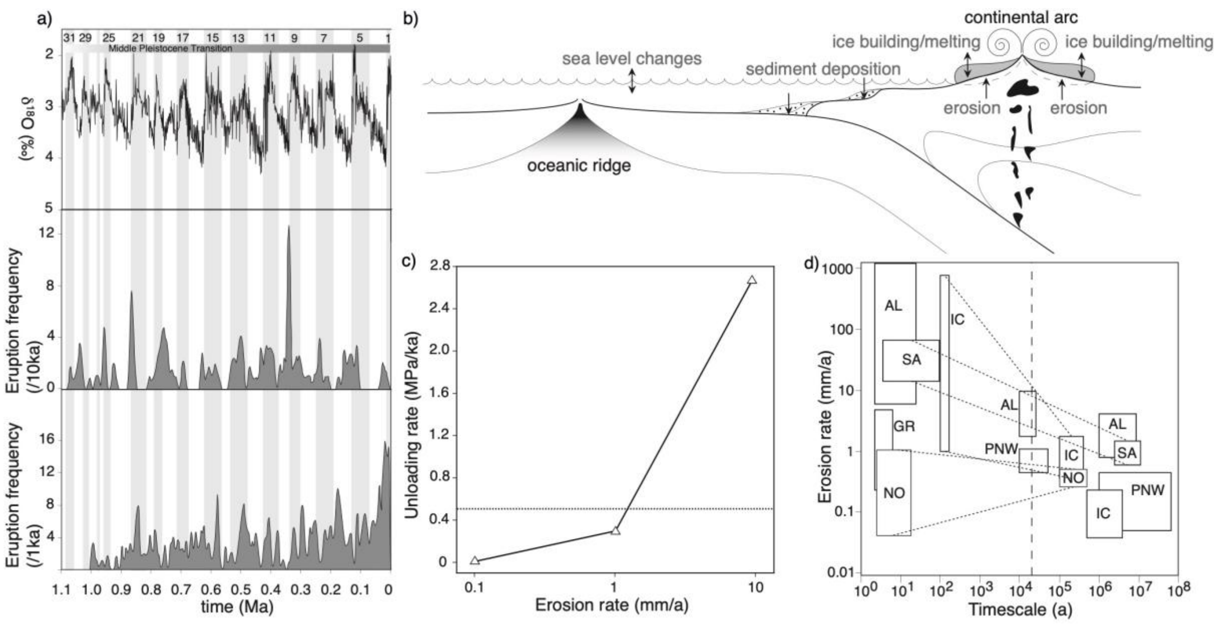

Figure 4: (a) Global $\delta^{18}O$ curve (Zachos, et al., 2001), tephra frequency at the Izu Bonin Mariana arc (central panel, using 10 ka binning after (Schindlbeck , et al., 2018)) and the Pacific Ring of Fire (lower panel, using 1 ka binning after (Kutterolf, et al., 2013)). The Middle Pleistocene Transition leads from dominant ~40 ka periodicity of climate oscillations to dominant ~100 ka cycles. Vertical gray bars mark marine isotope stages (MIS) after Railsback, et al., 2015. Note the cyclicity of the tephra record consistent with glacial-interglacial cycling. (b) Schematic representation of the relationships between surface processes (gray) and magmatic sources (black). Erosion, sediment deposition, ice building-melting and sea level changes can affect processes responsible for the production, transfer and eruption of magma by modulating the stress state at depth. (c) Estimated continental unloading rate owing to constant melting of 1km of ice (dotted line for reference) and erosion (assuming a surface rock density of 2,700 kg/m^3) throughout the last interglacial (Sternai, et al., 2016a). (d) Boxes represent ranges of erosion rates from glaciated catchments or proximal basins including errors in estimations (vertical) and resolved timescale (horizontal). The data is from Brandon, et al., 1988; Hallet, et al., 1996; Sheaf, et al., 2003; Reiners , et al., 2003; Koppes & Hallet, 2006; Hebbeln , et al., 2007; Geirsdottir, et al., 2007; Berger & Spotila , 2008; Koppes, et al., 2009; Cowton, et al., 2012; Herman , et al., 2013; Herman & Brandon, 2015. AL, Alaska; SA, Southern Andes; GR, Greenland; NO, Norway; PNW, Pacific Northwest; IC, Iceland. The vertical dashed line represents the approximate time since the LGM (Lisiecky & Raymo, 2007). At such timescale, erosion rates between 1-10 mm/a are commonly observed.

Ice building/melting and associated sea level variations during glacial-interglacial cycles affect the magmatic activity (Fig. 4a) modulating decompression partial melting (e.g., Crowley, et al., 2015; Jull & McKenzie, 1996), generating new fractures that facilitate the magma transport through the lithosphere (e.g., Rubin, 1993; Maccaferri, et al., 2011), and enhancing gas exsolution within volatile saturated magmas, thereby leading to overpressure and increasing the probability and magnitude of eruptive events (e.g., Jellinek & De Paolo, 2003). However, the link between erosional unloading of continent and partial rock melting or the transfer through the lithosphere and eruption of magma was not envisaged, although the density of rocks and sediments is about three times the density of water or ice and deep fjords, glacial over-deepened valleys, and the ubiquitous low-stand fluvial incisions on shelves testify for intense erosion associated with glaciation. Pulses of erosion at regional or local scales are commonly observed in the fluvial and glacial sedimentary records (e.g., Boulton, et al., 1988; Mullins & Hinchey, 1989; Bjornsson, 1996; Singer, et al., 1997; Brown & Kennett, 1998; Koppes & Hallet, 2006; Geirsdottir, et al., 2007) and numerical experiments (besides simple physical considerations) indicate that erosion rate in the order of the mm/a or higher during deglaciation unload continents by a similar or greater amount than the melting of large ice sheets (Sternai, et al., 2016a; Fig. 4b,c). Long-term proxies of global sediment efflux from mountainous regions show just such erosion rate variability and, at secular to millennial timescales, erosional fluxes may be even higher and subject to strong variations due to modifications of the subglacial hydraulic system and water supply (e.g., Koppes & Montgomery, 2009; Herman, et al., 2011). The abrupt and high-magnitude magmatic pulses involved by such erosional changes are likely to force centennial- to millennial-scale variations of atmospheric greenhouse gases seemingly unrelated to ocean dynamics (e.g., Monnin, et al., 2004; Marcott, et al., 2014). In fact, on a global scale, sea level rise following continental ice melting seems able to reduce the magma productivity of mid-oceanic ridges (e.g., Crowley, et al., 2015), in turn potentially buffering the increased subaerial volcanic activity and associated degassing owing to continental unloading by the deglaciation. Such a buffering effect, however, does not apply to continental unloading by erosion because sediment deposition in the ocean is unlikely to occur atop of oceanic ridges, which are, for the vast majority, several hundreds of kilometers away from continental shelves and stand up to a few thousand meters higher than abyssal plains or subduction trenches to where the eroded sediments are transported (Fig. 4b). Therefore, continental erosion may have greater net effects than ice melting on the CO_2 outflux and magma productivity from the solid Earth. Earth system models that do not account for erosion may lead to significant underestimations of the increase in atmospheric CO_2 concentration during interglacials (Sternai, et al., 2016a).

The possibility of a positive feedback between factors internal to the climate system such as erosion, subaerial volcano-magmatic CO_2 emissions, climate warming and deglaciation is particularly worth of investigations. In a recent publication (Sternai, et al., 2020), we suggest that such positive feedback may explain the “sawtooth” asymmetry (i.e., faster transitions to warmer conditions than cooling trends) of Plio-Pleistocene glacial cycles (e.g., Lisiecky & Raymo, 2007), which is not found in any orbital or insolation curve (e.g., Broecker & Donk, 1970). The main logic is that inhibition of subaerial eruptions during glacial periods forces accumulation of gasses in magmatic reservoirs, which are then released over a few thousands of years during the early interglacials (e.g., Jellinek, et al., 2004). Assuming that the long-term weathering CO_2 sink is at equilibrium with the steady state volcanic CO_2 outgassing, the weathering carbon sink slightly dominates over inhibited volcanic carbon emissions when ice sheets grow, leading to a temporary reduction of atmospheric CO_2, which sustains climate cooling. As soon as the orbital forcing of solar radiation overtakes the threshold to trigger the deglaciation, enhanced volcanic carbon outgassing dominates over the weathering carbon sink, in turn fostering climate warming and bringing the overall atmospheric CO_2 budget back to equilibrium. The concept may be expressed with an example based on the early Pleistocene 40 ka and late Pleistocene 100 ka glacial-interglacial cyclicity. If the phase of enhanced outgassing during early interglacials is extinguished in ~10 ka, then the cooling phase is forced to ~30 ka and ~90 ka for early Pleistocene and late Pleistocene cycles respectively. The ~10 ka time window is chosen arbitrarily, but the duration of warming of late Pleistocene climate oscillations and the expected response time of magmatic systems to surface load changes constrain this value (e.g., Jellinek, et al., 2004; Lisiecky & Raymo, 2007). Because both constraints are largely independent on the period of climate oscillations (i.e., 40 or 100 ka), the duration of the phase of enhanced outgassing determines the asymmetry of climate oscillations. That is, the longer the phase of gas accumulation in magmatic reservoirs (glacials), the larger the outgassing rate during the phase of enhanced emissions (early interglacials), and the more pronounced the asymmetry between warming and cooling trends (Sternai, et al., 2020). This is also consistent with increasing asymmetry of climate oscillations throughout the mid-Pleistocene transition from dominant 40 to 100 ka cycles (e.g., Lisiecky & Raymo, 2007). Of course, this simplistic analysis should be investigated further and possibly validated via observations and more thorough modeling.

4. A long way to go

Since at least the ’80, the recognition that major long term climate changes are related to geodynamic events boosted research on the feedbacks between internal and external dynamics and led to cross-disciplinary research efforts that built up most of our current knowledge on the topic. Increasing awareness about the current climate crisis since the early 2000s helped maintaining a considerable interest on the subject. Indeed, knowledge about the natural variability of climate and the interactions between geological processes behind them is a fundamental prerequisite to quantify the characteristic magnitudes and rates of anthropogenic climate and environmental changes. Although much has been done, there remain many poorly explored and likely fertile areas in this research field. I outline hereafter a few examples.

4.1. Feedbacks between internal and external dynamics in extensional settings

Much of what we know about the feedbacks between internal and external Earth processes and resulting climate-tectonics interactions comes from the study of mountain building in convergent tectonic settings. However, prominent topographic ridges and basins generated by dominant extensional tectonics make divergent settings valuable contexts too (e.g., Armijo, et al., 1996; Petit, et al., 2007; Sembroni, et al., 2016). In a recent online seminar (MCS RCN organized by the Community Surface Dynamics Modeling Systems), Susanne Buiter points out correctly that narrow and wide continental margins are commonly sediment starved and rich respectively, which indicates that surface processes, particularly sediment deposition, and the lithospheric extensional strain are related. The relationships that link surface processes and lithospheric strain in extensional settings were studied through numerical models that assume dominant hillslope-controlled erosion/deposition rates, $\dot{e}_{hill}$, commonly assessed via a linear diffusion law such that, $\dot{e}_{hill} = k\nabla^2 z$, where k is a scaling coefficient (also referred to as diffusivity) and z is the surface elevation (e.g., Burov & Cloetingh, 1997; Burov & Poliakov, 2001; Buiter, et al., 2009; Sternai, 2020). Numerical models indicate particularly that syn-extensional sediment deposition within rift basins produced opposite mechanical and thermal effects. The increase in vertical stress involved by the deposition of sediments within rifts basins enhances the lithostatic pressure and, thus, the brittle strength of crustal and mantle rocks. On the other hand, thermal blanketing by sediment deposition prevents crustal rocks to lose heat, thereby enhancing the viscous strain of the lithosphere (Fig. 5). By inhibiting localized brittle strain and favouring distributed ductile flow of viscous rocks, sediment deposition above a stretching lithosphere favours lateral migration of the extensional strain in turn allowing for prolonged stretching and delayed continental lithospheric breakup (e.g., Burov & Cloetingh, 1997; Buiter, et al., 2009; Sternai, 2020).

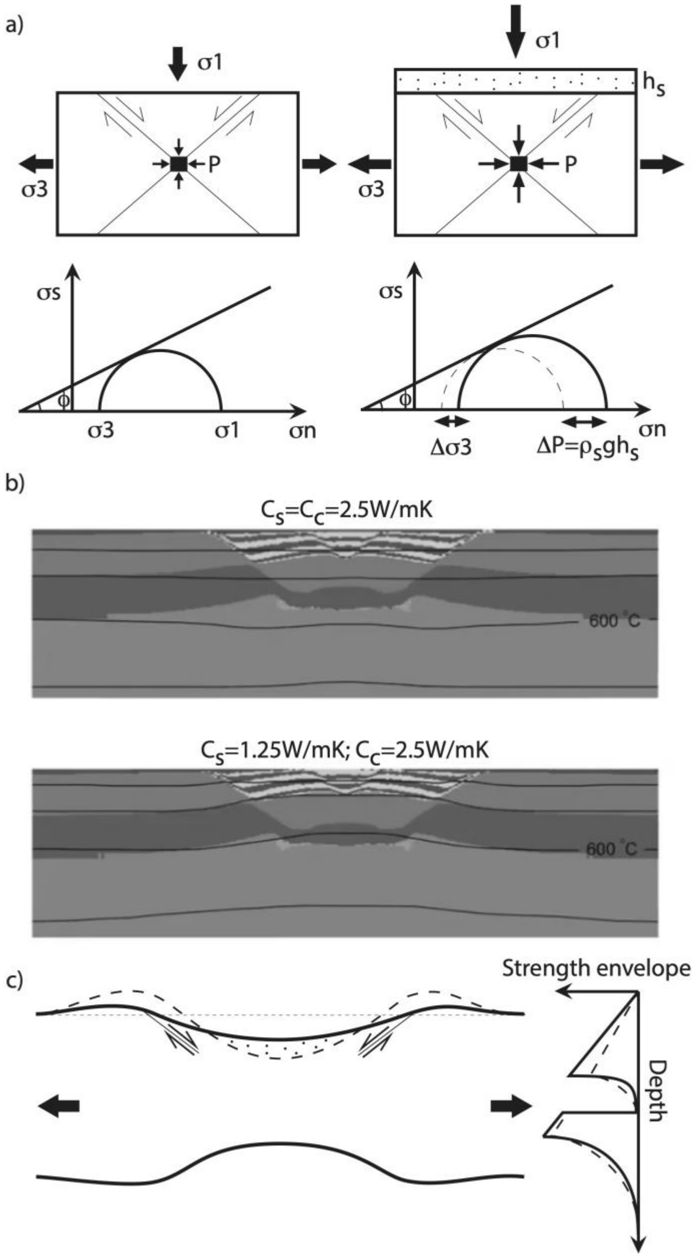

Figure 5: (a) Effect of surface loading by deposition of a layer of sediments, h_s, on the brittle strain during extension (σ_1: vertical stress; σ_3: horizontal stress; σ_n: normal stress; σ_s: shear stress; φ: rock friction angle; ρ_s: density of sediments; g: gravity acceleration). Enhanced lithostatic pressure, P, due to sediment deposition within rifts basins enhances the brittle strength of crustal and mantle rocks and a greater σ_3 is required to rupture brittle rocks. (b) Comparison between two numerical models from Buiter, et al., 2009, to which the reader is referred for more detail. The simulations account for the same thermal conductivity of crustal rocks, C_c, and sediments filling the rift basin, C_s, (upper panel) and lower thermal conductivity of the latter with respect to the former (lower panel), all other settings being the same. The thermal blanketing effect due to the low-conductivity sediment fill fosters the viscous strain of rocks (e.g., Buiter, et al., 2009; Sternai, 2020). (c) Schematic representation of the joint effects of surface processes on the brittle and ductile strain of lithospheric rocks during extension. Solid and dashed lines show the case with efficient and inefficient surface processes, respectively.

Syn-extensional and post-breakup magmatic units are nearly ubiquitous in extensional settings and in some cases particularly voluminous (e.g., White & McKenzie, 1989; Franke, 2013), which makes extensional settings even more appealing for the study of the feedbacks between internal and external dynamics. Magmatism likely provides a substantial contribution to lithospheric rupturing (e.g., Kendall, et al., 2005; Lavecchia, et al., 2016) because extensional stresses alone are estimated to be at most just enough to rupture the continental lithosphere (e.g., Bott, 1991; Buck, 2004). The magma supply within fracture zones increases the pore fluid pressure, thereby lowering the plastic yield strength of fractured rocks and further localising the strain and topographic uplift or subsidence along weakening fault zones (e.g., Turcotte, 1982; Spence, et al., 1987; Connolly & Podladchikov, 1998; Gerya & Yuen, 2007; Katz, 2008; Sternai, 2020). In this frame, peaks of igneous activity due to enhanced mantle decompression melting have been ascribed to surface unloading by the deglaciation (e.g., Jull & McKenzie, 1996; Singer, et al., 1997) and/or erosion (Sternai, et al., 2016a) or sea level lowering (e.g., Crowley, et al., 2015; Sternai, et al., 2017). However, the sensitivity of extensional systems to surface processes and the mechanisms that allow these latter to affect the production, transfer and emplacement or eruption of magma are poorly constrained. Numerical modeling suggests that flexural bending of the Moho due to efficient sediment delivery into a rift basin is an efficient mechanism to enhance crustal melting in a stretching and warming lithosphere (Sternai, 2020). Surface loading due to efficient filling of the rift basin, however, dampens decompression partial melting of the asthenosphere by an amount proportional to the rate of basin deepening/filling, the sediment density, and the surface-to-depth stress change transfer of the rift system. For a given erosion/deposition rate, the modulation by surface processes to rock melting in natural rift settings is inversely correlated to the extensional velocity, mantle potential temperature (*sensu* McKenzie & Bickle, 1988) and initial Moho depth. In the extreme case where surface processes redistribute the surface masses so efficiently to reset the topography through time (i.e., the rate of erosion/deposition equals the rock uplift/subsidence rate) the amount of crustal and mantle melts may respectively double and be reduced by ~50% (Sternai, 2020). These modeling results does not account for brittle-plastic strain localisation due to melts-rocks interactions (besides many other factors), so these estimates are likely conservative. Increasing observational evidence corroborates these modeling results showing that surface load changes in the order of the tens of MPa due to sea level changes during glacial interglacial cycles can modulate the extensional magmatism (e.g., Crowley, et al., 2015; Schindlbeck, et al., 2018; Kutterolf, et al., 2019; Satow, et al., 2021). Indeed, it seems somewhat intuitive that a stretching and thinning lithosphere transmits surface stress changes at depth more easily than a shortening and thickening lithosphere, implying that extensional systems should be even more sensitive to the surface mass redistribution by surface processes than convergent settings.

Bedrock fluvial incision plays a primary role in creating local relief in uplifting areas, and this is also true for extensional settings. Geomorphologists have long proposed that the bedrock fluvial erosion rate, $\dot{e}_{fluv}$, is proportional to the river stream power so that $\dot{e}_{fluv} = KA^m \left|\frac{dz}{dx}\right|^n$, where $\frac{dz}{dx}$ is the local slope, A is the river drainage area, and K is the rock erodibility, itself a function of precipitation and rock type (e.g., Gilbert, 1877). m and n are arbitrary exponents usually determined by fitting models to river longitudinal profiles (e.g., Whipple & Tucker, 1999; Sternai, et al., 2012). Although simplistic, the definitions of $\dot{e}_{hill}$ and $\dot{e}_{fluv}$ capture the main physics behind landscape evolution under hillslope- and fluvial-dominated conditions and, most important for this chapter, they provide a straightforward means to investigate feedbacks between the surface mass redistribution and lithospheric to sub-lithospheric dynamics. The hillslope diffusion law has the clear advantage to reproduce jointly erosion and sediment deposition and, thus, to better account for conservation of the surface masses. The classical stream power erosion law, instead, does not account for sediment deposition (i.e., no mass conservation) (e.g., Whipple & Tucker, 1999). Fig. 6 shows a rather crude comparison between the resulting extensional continental lithospheric and sub-lithospheric strain when hillslope or fluvial processes assessed via the diffusion and stream power erosion laws are dominant. The numerical setup is similar to that described in Sternai, 2020, and Sternai, et al., 2021, to which the reader is referred for more information. This comparison should be taken carefully because formulations of the stream power law that account for sediment deposition do exist (e.g., Yuan, et al., 2019) and they should be preferentially used for most applications. In addition, fluvial erosion leads to the formation of hillslopes along river channels and, thus, $\dot{e}_{hill}$ and $\dot{e}_{fluv}$ are interdependent and should be modeled jointly rather than alternatively or independently. However, the comparison shows that different surface mass redistribution histories imply different effects on the deep dynamics and, thus, informs us about the relevance of the physical treatment of surface processes in geodynamic modeling. The classical stream power law is more effective in localizing the cross-lithospheric strain, and even leads to earlier lithospheric breakup. However, this result is largely due to the lack of a sediment deposition term and, thus, is reliable only if the natural sediment routing brings the eroded material far out the extensional system. The main point is that typical changes in the temporal and spatial pattern of surface mass redistribution may result in protracted variations of the strain rate by up to a few orders of magnitude that reach down to sub-lithospheric levels. Such variations imply changes in the location and amount of partial rock melting, with further feedbacks on the strain pattern and topographic evolution. The resulting chain of cause-effect relationships between surface, lithosphere and asthenosphere dynamics are extremely complex and highly non-linear. I thus anticipate that unraveling the substantial modifications to the architectural evolution of extensional systems involved by ever-changing surface processes will be a tough but highly rewarding challenge for future research.

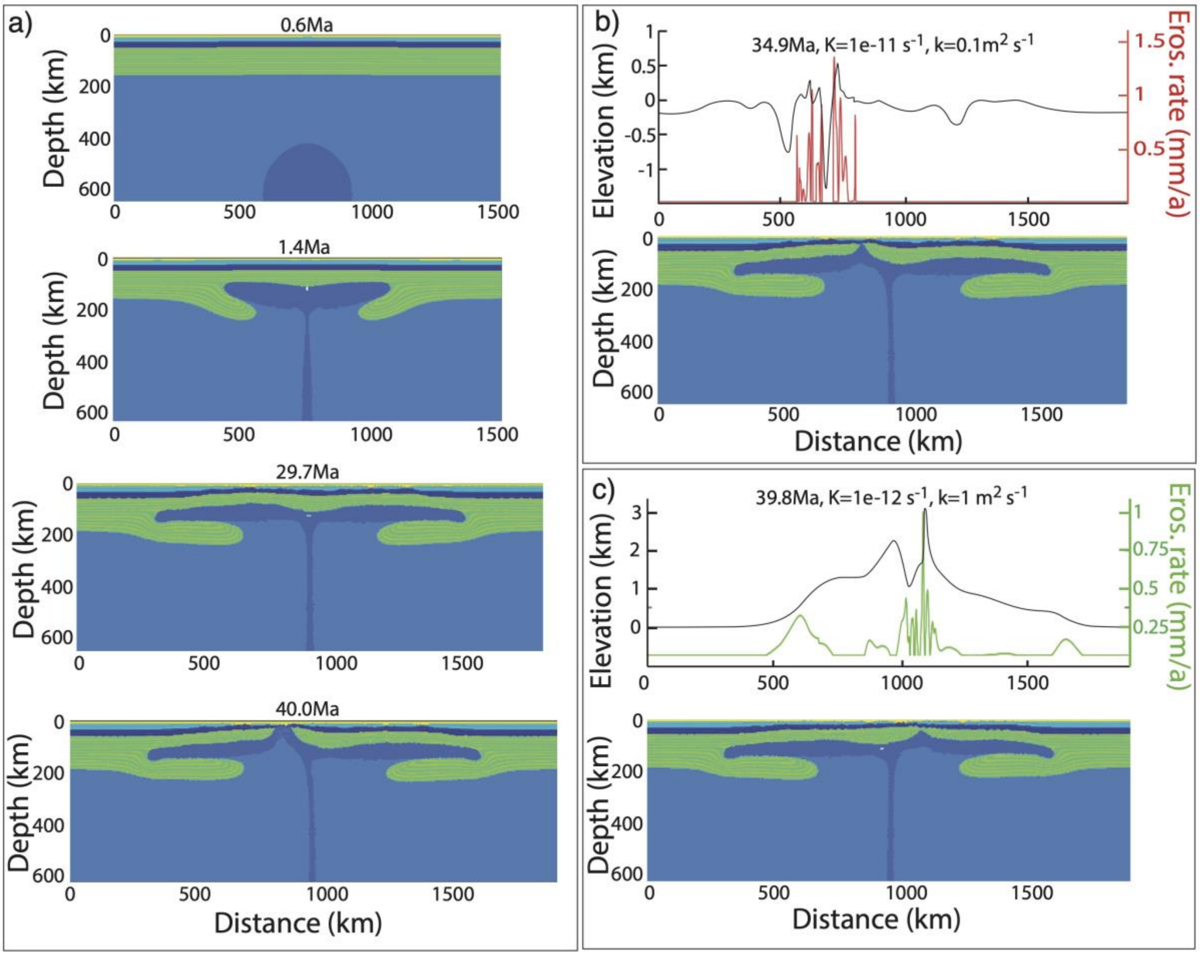

Figure 6: (a) Example of thermo-mechanical model of lithospheric extension above a mantle plume (the reader is referred to Sternai, 2020, and Sternai, et al., 2021, for more details on the numerical model). (b, c) Selected timesteps of simulations that account for different stream power or diffusion erosion rates (scaled based on K and k, as described in the definitions of $\dot{e}_{fluv}$ and $\dot{e}_{diff}$ reported in the text), all other settings being equal. The different redistribution of the surface masses through time due to different surface processes lead to major changes in, e.g., the location of lithospheric rupturing and, thus, the rift architecture and topographic evolution.

4.2. The geological carbon cycle

At timescales of millions to tens of millions of years, the Earth's carbon flows between the atmosphere, lithosphere, and mantle in an exchange called the geological carbon cycle (e.g., Berner, 2003; Broecker, 2018). Carbon emissions from volcanic arcs above subduction zones are a critical input of carbon into the atmosphere, whereas the chemical weathering of silicate rocks exhumed at the Earth's surface through erosion of tectonically uplifted terrains consumes the atmospheric carbon (e.g., Lee & Lackey, 2015; Kelemen & Manning, 2015; Mason, et al., 2017). By preventing all the Earth's carbon from entering the oceans and atmosphere or being stored within rocks, the geological carbon cycle keeps the Earth's temperature relatively stable on the long term, like a global thermostat, linking the evolution of life and climate to plate tectonics. The geological carbon cycle, thus, embodies the essence of the coupling between tectonic and climatic changes.

Analyses of the sedimentary archives allow assessing the carbon outflux from the atmosphere through erosion and chemical weathering. Instead, the uncertainty regarding the amounts and driving mechanisms of carbon recycling and emissions from the Earth's interior stands out as one of the most vexing problems facing us in understanding the geological carbon cycle (e.g., Berner & Lasaga, 1989; Dasgupta, et al., 2007; Burton, et al., 2013). Available estimates of current carbon fluxes between the Earth's deep and surface reservoirs, for instance, vary by several orders of magnitude (e.g., Dasgupta, et al., 2007; Kelemen & Manning, 2015), which is indicative of how little we know about this branch of the carbon exchange cycle. Multidisciplinary integrations of geological data and modeling to quantify variations in global carbon emissions due to fundamental geodynamic events throughout the Earth's history and their critical effects on climate change represent a top-priority challenge for future research on the natural carbon cycle, the quantitative understanding of which is also a fundamental objective of the International Panel on Climate Change - IPCC (www.ipcc.ch).

The challenge is harsh but not impossible, especially if focused on geological times for which there are well preserved observable records. I see in the Cenozoic an ideal time window for this research because the global tectonic and climatic framework are relatively well established (Fig. 7). The progressive closure of the Neo-Tethys and the rise of the Alpine-Himalayan range perturbed the global atmospheric and ocean circulation, leading to climate warming between ~60-50 Ma followed by unsteady cooling ever since (e.g., Ruddiman & Raymo, 1988; Ruddiman & Kutzbach, 1989; Le Houedec, et al., 2012). The development of high topography and closure of marine gateways alone are insufficient to cause the observed long term Cenozoic climate trends, and changes in the concentration of CO_2 and other radiative important gasses are required (e.g., Raymo & Ruddiman, 1992). Two end-member hypotheses exist: the overall changes in atmospheric carbon budget and associated Cenozoic climate trends are driven primarily by variations of global chemical weathering, the main atmospheric carbon output term, or by variations in global degassing by magmatic and/or metamorphic processes, the main input term. A currently established paradigm states that the India-Eurasia collision and uplift of Tibet led to intense monsoonal circulation, increased rainfall on the Himalayas, greater rates of rock weathering and, ultimately, lower atmospheric CO_2 concentrations and long-term Cenozoic climate cooling (e.g., Raymo & Ruddiman, 1992). This view is often associated with the proposal that Cenozoic climate cooling led to Plio-Quaternary increase in global mountain elevation and sedimentation/erosion (Molnar & England, 1990). This proposal embodies a true chicken or egg problem because erosion and weathering consume atmospheric carbon and thus would be the cause, rather than the effect, of climate cooling.

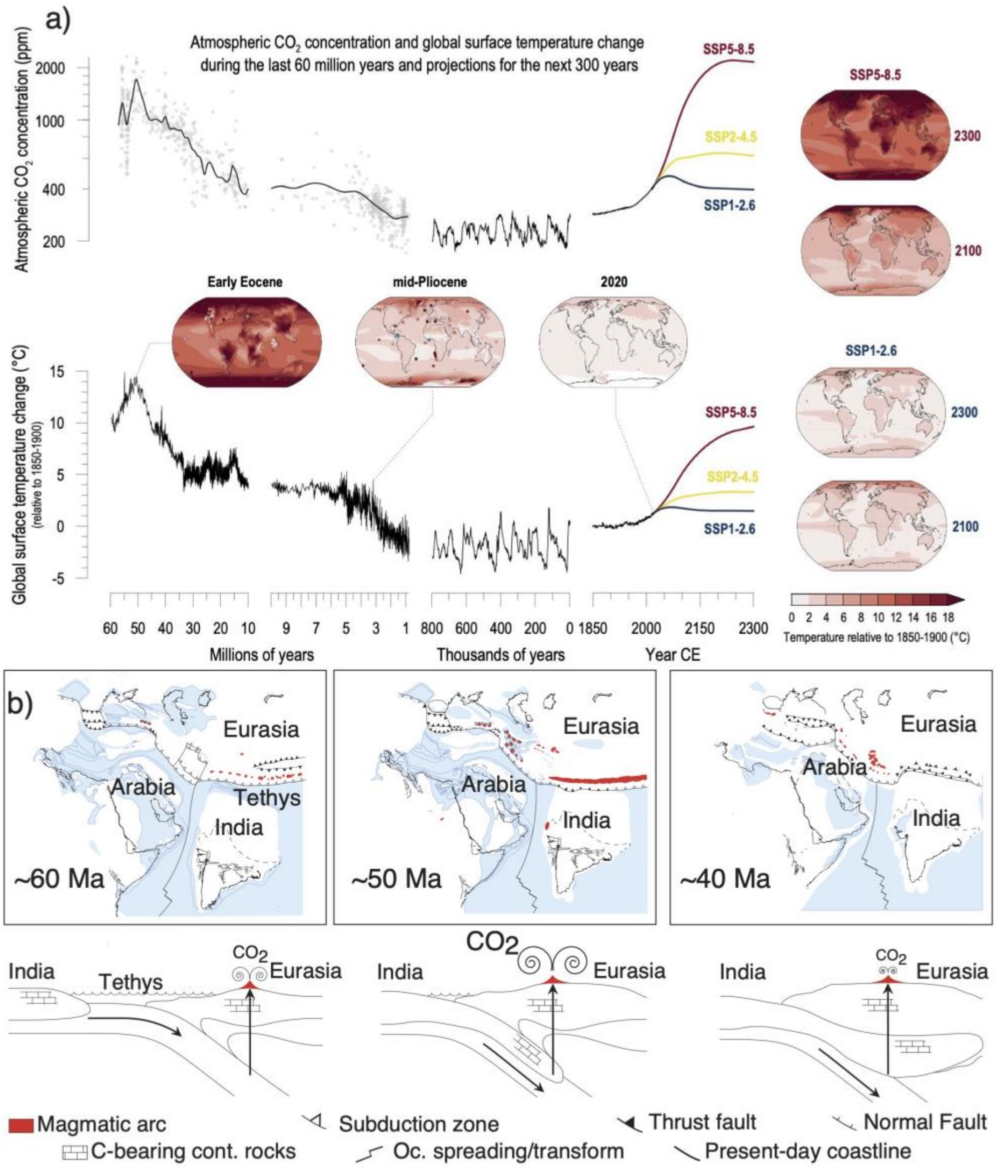

Figure 7: (a) Changes in atmospheric CO_2 and global surface temperature (relative to 1850-1900) throughout the Cenozoic and for the next 300 years (modified after [IPCC 2021 report], to which the reader is referred for details on sources and data analyses). (b) Paleotectonic maps and cross-sections of the Neo-Tethyan margin during the lower Cenozoic (modified after the paleotectonic reconstructions by the DARIUS program, 2018, http://istep.dgs.jussieu.fr/darius/maps.html and Sternai et al., 2020).

On the one hand, the increase in global weathering paradigm and the chicken or egg controversy motivated a huge amount of research that greatly advanced our knowledge on the tectonics-climate interactions from the weathering perspective (i.e., atmospheric carbon sink). On the other hand, the role of changes in continental degassing or organic carbon erosion and oxidization from marine sediments on the passive and active Neo-Tethyan margins during the early Indian-Asian collision (i.e., the atmospheric carbon source perspective) have been significantly overlooked (e.g., Beck, et al., 1995; Sternai, et al., 2020) and major climatic trends such as the early Eocene climate optimum (EECO, i.e., the ~10 Ma climate warming preceding post-50 Ma cooling) remain currently unexplained. I recently happened to assist a Professorship promotion where eminent geologists did not account that the India-Asia collision since the early Cenozoic involved the progressive demise of several thousands of kilometers of volcanic arcs which were continuously and likely unsteadily emitting carbon into the ocean and atmosphere since at least the Cretaceous. The entire Andean or Indonesian arcs today, which account for some of the greatest CO_2 outgassing volcanoes worldwide (e.g., Burton, et al., 2013), are modern analogues of these former arcs. I find it hard to believe that extinguishing emissions of greenhouse gasses from these arcs would leave climate unaltered. Recent studies further suggest that global Cenozoic silicate weathering fluxes weaker than previously thought (e.g., Tipper, et al., 2020) are, at least to some extent, compensated by weathering of accessory carbonate and sulfide minerals, a geologically relevant source of CO_2 (e.g., Torres, et al., 2017; Komar & Zeebe, 2021), suggesting that other factors must be at play. Plausible changes in CO_2 emissions from the Neo-Tethyan magmatic arcs during convergence are strikingly consistent with both the ~60-50 Ma climate warming and post-50 Ma cooling (Fig. 7), and there is a general agreement that Neo-Tethyan margin is key to global Cenozoic climate change (see e.g., Sternai, et al., 2020, for a review on the topic). However, other major geodynamic events involving likely significant climatic effects occurred worldwide during the early Cenozoic, for instance the propagation of Atlantic Ocean spreading along the Reykjanes Ridge or of East African Rift System (e.g., Seton, et al., 2012; Ebinger, 2005). I anticipate that integrated investigations accounting for magmatism as well will considerably broaden our knowledge about how plate tectonics affected the climate evolution. To this aim, quantification of the CO_2 content and petrogenic characterization of preserved magmatic products as well as integration between numerical geodynamic and thermodynamic models to explore how dynamic processes affect the transformations of carbon-bearing rocks in different geological settings can provide direct and quantitative constraints on CO_2 outgassing throughout the Cenozoic or longer timescales.

4.3. Feedbacks between internal and external dynamics and effects on the evolution of life

Several elements and nutrients useful to life (besides carbon) are cyclically transferred through surface and deep reservoirs during geological timescales. This implies that geodynamic events are intrinsically linked not only to the evolution of climate and the landscape, but also to the biosphere. Increasing evidence indicates that the establishment of modern-style plate tectonics contributed to the development of complex life on our Planet (e.g., DePaolo, et al., 2008; Sobolev, et al., 2011; Stern, 2016; Zaffos, et al., 2017; Lee, et al., 2018). A global continuously evolving mosaic of lithospheric plates, likely established gradually during the geological past (e.g., Gerya, 2014; Sobolev & Brown, 2019; Gerya, 2019), supplies and withdrawals nutrients and produces variations of environmental conditions that foster genetical modifications and thus the evolution of life (e.g., Zerkle, 2018; Descombes, et al., 2018). The redistribution of continents, the growth of mountains, the rise and demise of volcanic and magmatic arcs, the opening and closing of marine gateways also produce moderate environmental ‘stress’ that stimulates populations to adapt and evolve (e.g., Stern, 2016). Indeed, some of the characteristic timescales of biological evolution are comparable to those at which geodynamic reorganizations occur, which may be taken as further evidence of the coupling between internal and external dynamics (e.g., DePaolo, et al., 2008). Research efforts to quantitatively assess the mechanisms through which geodynamic processes influence the evolution and diversification of species are a natural and logical step forth to enhance knowledge on the feedbacks between internal and external dynamics and their multiple implications. To this aim, geodynamicists, geologists, (geo)biologists, ecologists, geochemists, palaeontologists, geomorphologists, and climate experts must cooperate to integrate/interpret biological data with geodynamic, landscape evolution, carbon cycle and climate (*sensu lato*) modeling. I anticipate that the necessary major cross-community efforts will lead to highly rewarding discoveries about our history and that of our Planet.

5. Closing Remarks

Recognizing and quantifying how and to what extent internal and external dynamics are linked has long been one of the grand challenges in the Earth Sciences (e.g., DePaolo, et al., 2008; Huntington, et al., 2017). Overtaking this challenge is more than ever critical now that warming temperatures, melting ice caps, rising sea levels, alteration of natural environments and biodiversity, increasing catastrophic events, and pandemics have become undeniable effects of the current anthropogenic climate crisis (IPCC 2021 report). It is essential to realize that our ability to face the current climate emergency and the threatening global socio-economic consequences entailed (Fig. 7) depends heavily on our understanding of the functioning of the Earth system. Monitoring ongoing climate change will help improving warning systems and the management and use of natural resources, but it will not improve our ability to anticipate cascading effects and act consciously and effectively to mitigate future events and re-establish the natural variability of climate. Only the study of the geological archives through ever-improving observations and modeling tools can elucidate on the causes and effects of the natural climate variability, thereby providing the baseline for understanding the current climate state and forecasting future changes. I thus believe that research on the feedbacks between internal and external dynamics will provide a critical help for decision makers for finding optimal policies to lead us out the ongoing emergency.

It is increasingly clear that in-depth understanding of the functioning of our Planet can only arise from the study of the atmosphere and oceans, but also of the landscape, the lithosphere, and the mantle not to mention our societies and social behaviour, which delve into it deeply. In fact, no problem of any significance can be perceived from within a single compartmentalised discipline, but also the smallest topic, however seemingly minute, can only be understood within and through its wider context. Complex systems commonly enhance and inhibit qualities specific to individual components and, thus, are at the same time more and less than the sum of their parts (Aristoteles, *Metafisica*). The significance of the study of individual parts is inversely proportional to the complexity of the system if one aims at understanding the functioning of the complex system itself. Trans-disciplinarity is an essential pre-requisite to understanding Nature (i.e., the Earth system). Although this may seem a trivial statement, a compartmentalized view of the Earth Sciences, where a scientist's work is meant to study the Discipline rather than Nature, is still very much present and severely limits new relevant scientific discoveries. I encourage any Earth Scientist concerned with the functioning of our Planet to engage into a 'complex' thinking that involves as many disciplines and, thus, collaborations as possible.

Since the advent of significant computing power, another just as harmful methodological distinction between 'modelers' and 'observational' Earth Scientists added up to the classical separation of the Earth Sciences into several compartmentalized disciplines. This distinction is pure nonsense. When a complex system such as the Earth is investigated, observations and models need to mutually draw meaning from each other. It is rarely straightforward to grasp useful information from geological observations because the functioning of the Earth, which is what generates those observables, is not so either. Most often, geological observables contain mixed information about multiple processes, and we need models to unlock this information. For instance, deformation structures into rocks contain information about the temporal and spatial evolution of the stress and thermal fields responsible for those structures, but obtaining such information requires a rheological model for rocks to say the least. Paleo-shorelines can contain information about the postglacial rebound, but obtaining this information requires a rheological model for the lithosphere and mantle as well as a model of the glacial ice sheet and sea level variations during the time window of interest. Sedimentary structures can contain information about eustatic changes, but obtaining this information requires a model for the sediment production, routing system and deposition, which itself may depend on a tectonic model that describes the evolution of the sediment source and sink areas. Just like doors need the right key to be opened, the information within geological observables cannot be accessed without the right model. Even trickier, the information delivered by geological observables can be very different, even wrong, depending on which model we use to access it.

Modern computers allow us to generate and handle extremely complex numerical models, which means we have increased potential to obtain useful information from observables. We can even generate synthetic 'observables' that inform us about inaccessible parts of the Earth or theoretical scenarios involving processes and interactions of processes that we cannot observe directly. If used correctly, then recent numerical models can be for Earth Scientists what a wind tunnel is for Engineers, that is a tool to test to test the response of a specific system to given forcings (i.e., the 'performance of a prototype', in engineering terms) as a term of comparison for real observations, or as synthetic data in absence of observations. Whereas there is usually no aversion toward simple models, complex models are often regarded to as science-fiction. Clearly, any scientist loves the sight of a straight line of data points because it can be fit by a linear (i.e., simple) model. However, observations that report on the functioning of the Earth system are practically never aligned, nor they should be because they arise from complex interactions between complex processes. Interpreting these data with too simple a model (e.g., linear regression) may bring wrong information leading to flawed conclusions just as much as interpreting the data with too complex a model that includes multiple poorly constrained parameters. Being aware of the flaws and limitations of our data and models (e.g., van Zelst, et al., 2021), rather than dismissing one or the other, should be the main concern of Earth Scientists, regardless of their observational or modeling background.

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